

ION CYCLOTRON RESONANCE: GEOMAGNETIC STRATEGY FOR LIVING SYSTEMS?

A R Liboff, Professor Emeritus, Department of Physics, Oakland University, Rochester, MI.

561 699-2079. 16766 Knightsbridge Ln, Delray Beach, FL 33484.

Abstract. Except for relatively few polarity reversals the magnitude of the magnetic dipole moment of the earth has remained constant since life first began, thereby allowing evolutionary processes to integrate the geomagnetic field (GMF) into several biological functions. The adaptation of ion cyclotron resonance (ICR) is manifested in enhanced proton transport. The surprisingly wide range of biomolecular masses exhibiting ICR suggests a very basic dependence on the GMF, one that may function equally well for electric and magnetic fields. Such generalization of ICR requires two things: transparency of tissues to the GMF and suitably tuned ELF resonant magnetic or electric fields. To complement the widely reported ICR responses to applied AC magnetic fields, we hypothesize the existence of weak endogenous ICR electric field oscillations within the cell. This equivalence implies that even in the absence of applied AC magnetic fields, biological systems will exhibit intrinsic GMF-dependent ion cyclotron resonance intracellular interactions. The many ICR effects that have been reported and the fact that these often appear as antagonist pairs suggest that the GMF has been incorporated into the genome as an endocrine-like magnetocrine system that generates frequency-specific electrohormones.

Introduction. To date, the geomagnetic field has not been considered a key factor in biology. The few interactive effects with living things, e.g., those involving animal navigation (Wiltschko & Wiltschko, 2002) and magnetic bacteria (Frankel et al, 1979), have been regarded as phenomenological and specific to certain organisms. Even the numerous observations surrounding both ion cyclotron resonance (ICR) effects (Liboff, 1985;2007) and retinal cryptochrome magnetosensitivity (Mouritsen et al, 2004; Gegear et al, 2008) are not usually thought of in geomagnetic terms but rather as still unresolved problems in molecular biophysics.

However the biological relevance of the GMF may be quite important, given that the magnetic dipole of the earth, save for relatively short-lived polarity reversals has been otherwise constant for billions of years (Tarduno et al, 2015). Worth noting is that the GMF field in its present form, with a surface intensity ranging from roughly 25-65 μT , has been part of the planetary environment for a time close to the first appearance of life on earth (Dodd et al, 2017), and far preceding the first appearance of the worldwide

abundance of atmospheric oxygen (Holland, 2006). It goes without saying that there has been more than enough time for evolutionary processes to have integrated the GMF into biological processes.

In the following we offer the argument that life on earth is especially dependent on the GMF. In particular the biological usefulness of this field derives from the fact that weakly intense static magnetic fields pass through tissue without absorption, exposing even the innermost cellular components to the identical magnetic intensity everywhere within the cell. This uniformity of field has the effect of providing a sharply specific basis for cell-wide interactions shared both intra- and extra-cellularly. This allows one to invoke the possibility of ion cyclotron resonance not only for cell-wide interactions, but also for multi-cell modes of information transfer (Foletti et al, 2013).

ICR and Proton Hopping. It has been recently hypothesized (Liboff et al, 2017) that the effectiveness of ion cyclotron resonance in living systems is connected to the long-standing question of proton-hopping (Agmon, 1995). This is in part suggested by the fact that only cations have been reported as sensitive to ICR stimulation. A number of reports indicate that not only does ICR exposure of water result in sharply increased electrical conductivity (Mohri & Fukushima, 2003; D’Emilia et al, 2017), but a similar effect is found in the resonance exposure of living tissue (Liboff, 2007). Increased electrical conductivity is readily associated with the phenomenon of proton hopping.

The details of the hypothetical connection between ICR-related biological effects and proton hopping rest on the associated structural changes in vicinal water structures adjacent to the stimulated cation. Hydronium ions in this nearby water are affected by the associated magnetostatic field, following a helical path conforming to the rotating electric dipole established by hydronium and the hydroxyl ion (Liboff et al, 2017). The net effect is the associated transport of protons usually described as proton-hopping, but with a path slightly different from how this effect is usually described, helical instead of simply directional.

Proton transport, of fundamental importance in biology (Aoi & Marunaka, 2014), plays a key role in a wide variety of expressions, ranging from oxidative phosphorylation and immune response to bioluminescence (Miyake & Rolandi, 2016). One reasonable explanation for the effects observed in ICR stimulation is that the response of living tissues to ELF weak ICR-tuned magnetic fields frequencies is related to enhanced electric conductivity. *In short, ICR effects are likely the result of enhanced proton transport.*

Contrasting B-field and E-field Ion Resonances. In physics the phenomenon of ion cyclotron resonance is obtained equally well for time-varying magnetic fields as for time-varying electric fields, for the case where

both types of field are generated at the same resonance frequency, the sole difference being the relative orientation of the E-and B-fields (Liboff, 1997) with respect to the magnetostatic field (Fig.1). The fact that magnetostatic fields do not interact with living tissue except insofar as they provide a means of selective resonance carries great significance in this regard. Indeed this is the primary reason for ion cyclotron resonance processes in living things, as expressed for both time-varying magnetic fields and time-varying electric fields.

One can estimate the electric-field intensity for such an ICR equivalent application by first assuming that the energy contents of the resonant electric and magnetic fields are the same. This is achieved by setting the magnetic field B energy density equal to the electric field E energy density, or by writing $B^2/2\mu_0 = \epsilon_0 E^2/2$, where μ_0 and ϵ_0 are respectively the permeability and permittivity of free space, universal constants that are related through the velocity of light, as $c^2 = 1/(\epsilon_0 \mu_0)$. This allows us to express in mks units the relation between an ICR magnetic field B and its equivalent ICR electric field as simply $E = cB$.

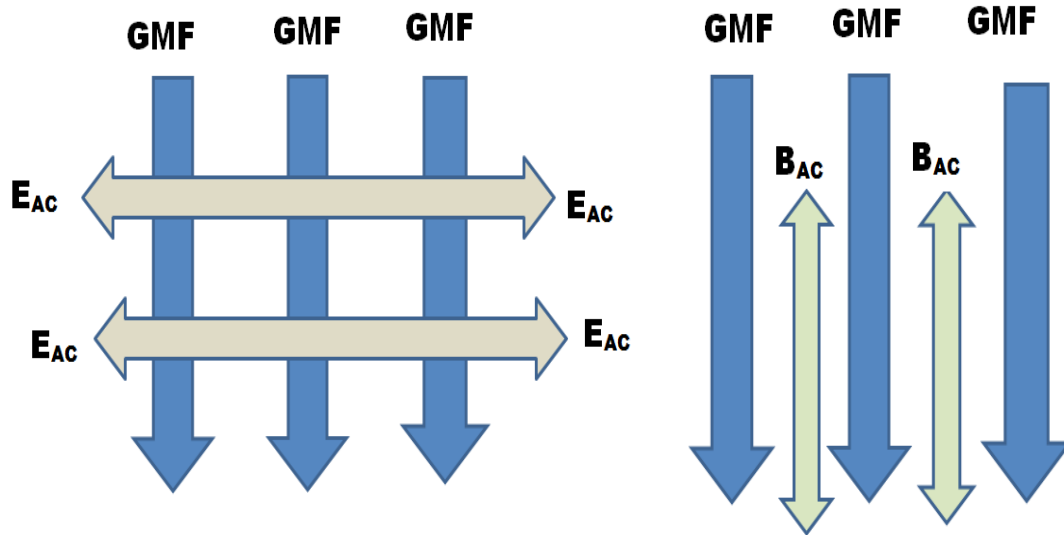


Fig. 1. The two equivalent orientations of a weakly intense ELF electric-field (E_{AC}) or ELF magnetic-field (B_{AC}) relative to the static geomagnetic field (GMF) either one of each can result in ion cyclotron resonance.

The latter expression enables one to find the range of expected electric fields E_{AC} equivalent to that of those time-varying magnetic fields B_{AC} that have been reported in ICR experiments. The smallest B_{AC} reported is that used in the highly replicated experimental result first obtained by Zhadin et al (1998) where changes in the aqueous conductivity of glu^+ were found for

the vanishingly small magnetic field of 40 nT. Multiplying by the velocity of light this equivalent electric field E is $3 \times 10^8 \times 40 \times 10^{-9} = 12 \text{ V/m}$. The upper end of AC magnetic intensities utilized in ICR experiments is about 1000 times larger, or 40 μT , corresponding to $12 \times 10^3 \text{ V/m}$. Thus the range of expected ICR electric fields is roughly 10 V/m to 10^4 V/m , from which it follows that even the largest ICR electric fields are well below the 10^7 V/m cell membrane electric field. Thus the magnitudes of electric field consistent with ICR intracellular interactions are not large enough to impact the insulating nature of the protective cell wall

Cellular Electric Field Oscillations. Electric-field ICR effects fully equivalent to those resulting from magnetic ICR fields are therefore possible with intensities that are orders of magnitude below that of the cell membrane electric field. This begs the question as to the origin of such intracellular electric fields E_{AC} that are required for resonance. These are likely associated with numerous cellular oscillatory states that have been widely reported (Pohl, 1983). Other than in the Central Nervous System (Buschman et al, 2012), oscillations are often described in ways that do not explicitly involve the E-field, but rather as chemical changes involving specific molecules. Although it is difficult to conceive of any local change in living systems, oscillatory or one-time, which is isoelectric, i.e., not involving some measure of change in electric-field, such changes in field are not necessarily oscillatory. Our proposed E_{AC} concept requires that electric-field oscillations are already in place, perhaps not reported earlier because they were too weak.

A number of electric field intracellular oscillations have already been observed or proposed. Most interesting, from the standpoint of our present work, are the electrical oscillations widely associated with microtubules (Pohl, 1983). Although usually thought of as generating very high frequencies, in the tens of GHz (Pokorny et al, 1998; Tuszynski et al, 2005), their structure and size could also readily be the source of ELF electric fields (Sirenko et al, 1996). Worth considering is the possibility that microtubule oscillations occur in a systematized synchronous manner over many single units. Other potential sources of oscillatory electric fields include those occurring in mitochondrial membranes (Aon et al, 2008), calcium oscillations (Berridge, 1993; Berridge et al, 1999; Schuster et al, 2002), and Belousov-Zhabotinsky reactions (Zhabotinsky, 1984; Winfree, 1984; Blank & Soo, 2003). Clearly, despite the lack of further specificity the living cell exhibits a variety of intracellular ELF oscillatory electric fields that could conceivably serve as sites for E-field ion cyclotron resonances.

Extended Cation Masses. Following the initial ICR studies, which involved simple atomic ions such as Ca^{2+} , K^+ , and Mg^{2+} (Liboff, 1985, Smith et al, 1987, Rozek et al, 1987), it was shown by Zhadin et al (1998) that more complex molecular ions, in particular the amino acid glu^+ , were similarly sensitive to resonance stimulation. Subsequent studies revealed that other large charged molecules, e.g., NAD^+ (Novikov et al, 2010) and H_3O^+ (D’Emilia et al, 2017), were also sensitive to ICR excitation. Thus, ion cyclotron resonance effects are observed over a wide range of ionic masses, extending over three orders of magnitude. This suggests an effect that is not phenomenological, but rather a more fundamental, widely applicable biological interaction involving the influence of the GMF on a great many key charge-sensitive reactions.

Although it is tempting to think of this wider effect as a sort of geomagnetic homeostasis, more detailed analysis suggests something else. The notion of homeostasis in biology essentially provides a number of autonomic pathways that serve to maintain the proper “setpoint” of the individual system. One commonly used example of homeostasis is the use of sweating to help keep the body temperature from going up. ICR stimulation is clearly different from homeostasis, in that in the latter case attempts are made to maintain the state of the system whereas ICR serves to alter the biological state. In one sense the action of the ICR field is similar to what the endocrine system does, in that biochemical changes are made that direct a specific part of the system one way or the other, providing pairs of antagonistic hormones (insulin/glucagon, estrogen/androgen, diuretic/vasopressin...). The difference is that instead of selected chemicals we find interactive resonance frequencies. Because the effect of ICR magnetic fields is to direct the system in specific ways, the net effect can be likened to electromagnetically-induced hormonal activity. Hence the term: *electrohormones*.

The literature provides a number of excellent examples of such hormone-like effects. Indeed this was well illustrated in the early widespread ICR experiments on rat behavior, which revealed that Ca^{2+} resonance exposures reduced memory function and enhanced passivity while K^+ ICR exposures tended to improve memory function and increase aggressiveness. A more complete listing of experiments indicating a number of such antagonistic pairs is given in Table 1.

MODEL SYSTEM	REFERENCE	FREQ Hz	B_{DC} μT	ION	RESPONSE
Diatom Motility	McLeod et al	16 16	20.9 41.0	Ca^{2+} K^+	Motility Up Motility Down

	1987				
Embryonic Bone	Smith et al 1991	16 16	20.9 41.0	Ca²⁺ K⁺	Growth Up Growth Down
Plant Growth	Smith et al 1993	60 60	78.3 153.3	Ca²⁺ K⁺	Growth Up Growth Down
Rat Learning	Lovely et al 1993	60 60	48 27	Mg²⁺ Ca²⁺	Faster Learning Slower Learning
Rat Behavior	Zhadin et al 1999	63 38	50 50	Mg²⁺ Ca²⁺	More Active Less Active
Root Gravitropy	Belova & Lednev 2000	35.8 54.7	46.5 46.5	Ca²⁺ K⁺	Growth Up Growth Down
GAGS Concentration	Regling et al 2002	16 16	20.9 40.7	Ca²⁺ K⁺	More GAGS Less GAGS

Table 1. ICR effects in various model systems, each effect with a clearly evident antagonist response suggesting that these frequencies can be regarded as electrohormones. Note that this set of results involve different ICR settings for merely three simple cations (Liboff,2005).

Discussion. One of the many puzzling things about the long list of ion cyclotron resonance reports, apart from the overarching problem of exactly how cyclotron resonance paths can be obtained in the fairly dense fluids found in biological systems, is the difficulty in considering an effect that is dependent on the Lorentz force, a force that is nonexistent for charged particles that are not in motion. The Lorentz force explicitly includes the term $\mathbf{v} \times \mathbf{B}$. This term not only provides a direction for the resulting force, namely perpendicular to both $\mathbf{v}$ and to $\mathbf{B}$, but it also requires that the charged particle is moving. There is evidence for motion of the net positive charge associated with simple cations such as Ca^{2+} , K^{+} , Mg^{2+} , under conditions where ICR effects have been reported. In these cases one can simply argue that charge transport occurs because the ion itself is in motion, a statement consistent with the accepted biological notion of ion transport as a signaling mechanism. However as we have discussed above, ICR is also observed in much more massive charged molecules that are not biologically effective because of their transport but rather because they contribute electrically positive charge to specific reactions. We conclude that ICR effects do not arise solely as a secondary consequence of ion transport.

One way of resolving this question is to suggest that ion cyclotron resonance effects are limited to those biological reactions already underway, where it can be assumed that some degree of charged particle motion is happening, even if this is only a loosely bound hydrogen charge. Although this seems to be at variance with the ICR eigenfrequency requiring that we must consider the entire mass of the stimulated molecule, this picture fits in precisely with the notion of proton-hopping, where many identical molecules merely transfer protonic charge. Thus, we postulate that the ICR reactions in living systems include some degree of actual motion for positively charged components. This is again consistent with our earlier comments linking ICR interactions with the phenomenon of proton-hopping.

We also note that in order for ion resonance to occur there must be an interactive process already at hand. This idea can be further generalized by associating an appropriately changing electric field with this process, thereby making it possible for the GMF to resonantly couple to the process in a manner described above as E_{AC} ICR. This allows us to view ICR interactions, nominally induced by the application of suitably tuned magnetic fields, as fundamentally electric in nature. The ICR effect, in other words, necessarily requires a corresponding electric field at the local level.

The most remarkable thing about the generalized ICR concept we have described is that it reveals the pivotal importance of the GMF in biology. A number of factors combine to suggest that the long-time constancy of this field has enabled it to be inextricably interwoven into life on earth, to the point where it serves a key role in biological function. We can refer to this heretofore unrecognized component of living things as the *magnetocrine system*. Similar in function to the well-known endocrine and exocrine systems, it generates regulatory pathways for the biological entity in the form of frequency-specific electrohormones. The *magnetocrine system*, analogous to the endocrine system, provides an additional means for advancing or retarding specific components of the overall system beyond mere homeostasis. It functions even in the absence of applied time-varying magnetic fields but it always requires the presence of a magnetostatic uniform field.

The present work adds to the notion that certain intrinsic biological properties are functionally dependent on the long-term constancy of physical components of the environment. The best example, of course, is the sun. DNA expression has been uniquely shaped by billions of years of exposure to the sun's light, to its delivery of heat, even to visual processes being primarily sensitive to the maximum wavelength in the solar spectrum (Stair et al, 1954). Most, if not all, living things are sensitive to the rate of spin of the earth, as evidenced by diurnal metabolic cycles. The force of gravity manifests itself in skeletal structures using piezoelectric proteins such as collagen to satisfy Wolff's Law (Wolff, 1892; Frost, 1994), ensuring greater

bone growth with increasing loading (McElhaney, 1965; Marino and Becker 1970). The present work adds the geomagnetic field to those long-term earth-specific constraints that have helped contribute to life on earth. Above all, the fact that the geomagnetic field enjoys a prominent biological role is consistent with our belief that despite widespread reliance on biochemistry and molecular biology to describe living systems life at its core is a manifestation of the electromagnetic field.

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